Appendix A
Heat-flux sensor: Laboratory procedure manual

HFMLP1:   **Kendall Radiometer Operating Procedure**
HFMLP2:   **Heat-Flux Sensor Calibration Procedure**
HFMLP3:   **Data reduction procedure**

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Kendall Radiometer Operating Procedure

Figure A1. ESR control unit front panel

1. **Radiometer/Controller set-up**
   a. Radiometer controller power-switch in off-position
   b. Connect radiometer Bendix cable to controller, & controller power cable to mains
   c. Cover the radiometer front end with the cap
   d. Connect the cooling water-pump outlet to the radiometer inlet
   e. Connect cooling water-pump inlet & the radiometer outlet to the coolant reservoir
   f. Adjust the dial on the pump flow-controller to a flow-rate of 0.5 L/m or higher
   g. Switch-on radiometer controller power
   h. Allow about 20 min for stabilization

2. **Digital voltmeter check-out (as and when needed)**
   a. Set switch "S1" to "OPERATE"
   b. Connect a Standard voltage source to the BNC input connector
   c. Set switch "S2" to "ZERO" position
   d. Turn DVM's "ZERO" adjust potentiometer to set the read-out to zero
   e. Set switch "S2" to "SCALE" position
   f. Adjust DVM's "SCALE" potentiometer to read the standard voltage source value.

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3. **Dark signal**
    a. Set both the switches "S1" and "S2" to "OPERATE"
    b. Allow the unit to stabilize for about 20 min
    c. The steady read-out gives the dark-signal value
    d. Turn the "TARE(R17)" adjustment potentiometer to set the read-out to 0.000

4. **Radiometer self-calibration & Operation (See note)**
    a. Set switch "S1" to "SCALE" position, and set switch "S2" to "VOLTS" position
    b. Turn potentiometer "HEATER-R16" to adjust to the desired voltage
    c. Set switch "S2" to "VOLTS" position: Note the voltage "V" on the meter
    d. Set switch "S2" to "CURRENT" position: Note the heater current (I) in mA
    e. Calculate electrical power $(P_c) = V$ (Volts) x I (mA) x C_f (=0.9925)
        [C_f is the radiometer aperture area (cm^2). For the radiometer in use C_f = 0.9925]
    f. Set switch "S2" to "OPERATE" position
    g. Allow the read-out to stabilize: Note the indicated power P_i on the meter
    h. If $P_i \neq P_c$, adjust potentiometer "SCALE(R18)" to set read-out P_i, to P_c
    i. Set both the switches "S1" and "S2" to "OPERATE" position.

Note: The radiometer self-calibration is at a power level $\approx$ 920 mW corresponding to the calibration power level used in the laser facility. The radiometer calibration gives the actual heat flux value.

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Heat-flux Sensor Calibration Procedure

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┌─────────────────────────┐
│        CAUTION          │
├─────────────────────────┤
│       COLLISION         │
└─────────────────────────┘
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1. **Calibration set-up**

   a. Remove the standard graphite tube extension on the viewing end of the VTBB and replace it with the short extension.
   b. Locate/align the reference ESR and the test-sensor at a fixed distance from the VTBB exit using standard gage blocks[3]
   c. Note down position values for the Aerotech-stage corresponding to the ESR (**Station-1**) and the test sensor (**Station-2**) location when aligned with VTBB axis
   d. Identify another position (**Station-3**) away from the ESR and the sensor, to station VTBB while being heated or cooled
   e. Connect cooling water pump to the ESR and set the flow-rate to 0.5 L/m or higher
   f. If the test-sensor is water-cooled, make appropriate cooling arrangements as per manufacturer's specification
   g. If the test-sensor has body-temperature thermocouple, connect the leads to Fluke thermometer to monitor body temperature during testing
   h. Connect analog output of the control unit to **Channel-1** of the HP multi-meter 3457A
   i. Connect the sensor signal leads (or the amplifier output) to **Channel-2** of the HP multi-meter 3457A
   j. Check connections, signal-polarity and instrument-cooling for proper functioning
   k. Record dark signals for the ESR and test sensor for about 60 s.

   continued

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[3] Recommended location of the sensor from the blackbody exit is 12.5 mm, 62.5 mm and 140 mm for calibration up to about 50 kW/m^2, 25 kW/m^2 and 10.0 kW/m^2, respectively.

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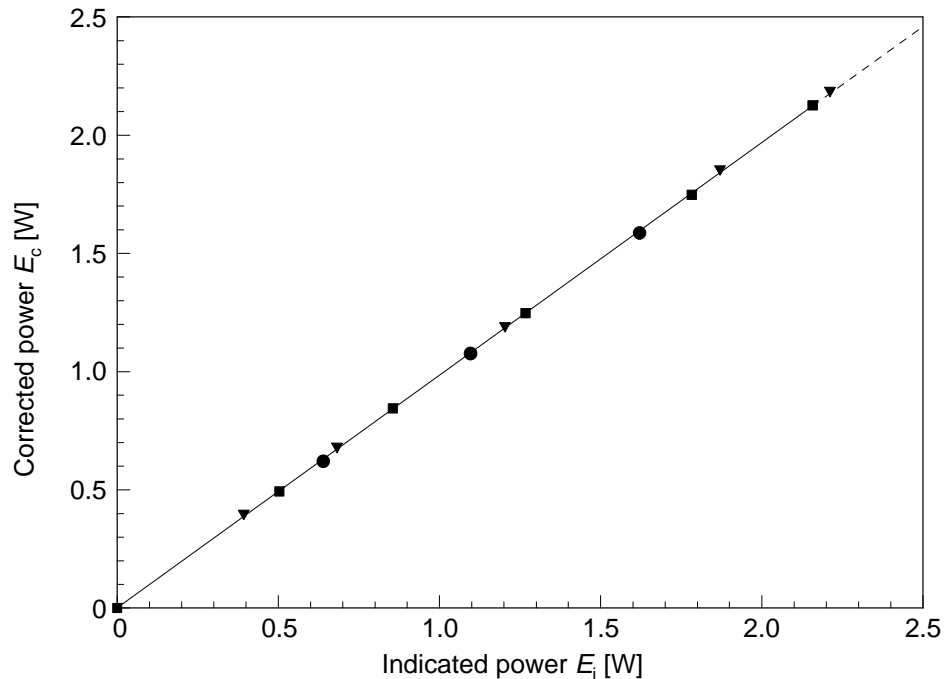**Heat-flux Sensor Calibration Procedure**
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2. Calibration Measurements

CAUTION
BRIGHT SOURCE
BURN
ELECTROCUTION

IMPORTANT
Prior to calibration of test-sensor, perform a check out calibration on the reference sensor

a. Record laboratory temperature and humidity
b. Locate the VTBB at **Station-3**

c. Turn on the VTBB as per procedure in manual **RTMLP11.1**
d. Set the desired temperature(**Table 4**) and allow the VTBB to stabilize
e. Move the VTBB in front of the ESR located at **Station-1**
f. Allow about 60 seconds for the ESR readings to stabilize
g. Record ESR output for about 20 s to 60 s depending on the heat-flux level[4,5]
h. Move the VTBB to **Station-2** in front of the test sensor
i. If the sensors are not water-cooled, **go to Step (l)**
j. Water-cooled sensors: Record output signal for about the same duration as ESR
k. **Go to Step (m)**
l. Data taking duration: Limited by the sensor body-temperature increase with time. Monitor body-temperature-rise when exposing to radiant heat flux.   Limit exposure time to about 10 s or less at high heat flux levels.

m. Move the VTBB to **Station-3**
n. Set VTBB temperature to the next value of heat flux and wait till stabilization
o. Follow **Steps (e) to (m)** till completion of calibration range

p. At the end of calibration, move the VTBB to **Station-3**
q. Shut down blackbody following standard procedure in the Laboratory
r. Remove the radiometer and the test sensor from the setup. Inspect to ensure the instruments are in good condition

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[4] > 60 s at heat-flux of 10 kW/m^2, 20 s or lower at 50 kW/m^2 when the distance between the blackbody and the sensor is 12.5 mm. About 10 s to 20 s when the distance is 62.5 mm or higher
[5] Note: Use a suitable file name to store the radiometer and sensor output data for later analysis

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Data reduction procedure

1. Calculate the mean value of the radiometer output (E_i) in W/cm^2, and the test-sensor output (V) from the data for each temperature setting of the blackbody.
2. Subtract the dark signals from the mean values calculated in **Step-1**. For calibration at high heat flux levels, the dark signals are small compared to the signal levels.
3. Calculate statistical quantities of interest such as standard deviation of the mean, from the radiometer and sensor output readings to calculate measurement uncertainty.
4. Convert the indicated radiometer mean value (E_i) to corrected radiometer power (E_c) by using the relation by $E_c = \mathbf{0.9855} \times E_i$ [See Fig. A2]
5. Express sensor output in **mV**
6. Perform a linear regression analysis for the heat-flux ($\mathbf{E_c}$) and the sensor output **(mV)** The slope of the linear regression gives the responsivity of the sensor in **mV/(W/cm^2)**
7. Plot the calibration data as shown in **Fig. 5** for the reference Schmidt-Boelter sensor.
8. Calculate measurement uncertainty in the calibration as listed in **Table-5**

Note: For calculation of mean value, standard deviation, and standard error, use a spreadsheet or other statistical software.

Figure A2. ESR calibration [1]